Scalar Rayleigh Dark Matter

Hadron colliders in the future experiments landscape

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In collaboration with: *Barducci, Buttazzo, Dondarini, Franceschini, Mescia, Panci*

FCC-hh Studies for the next European Strategy: Kickoff meeting | 2024

Motivation

- Even if DM is neutral under EM ⇒ interactions with EW gauge bosons via higher dimensional operators
- DM-photon EFT classification in [1] we analyze effective interactions involving real scalar $SU(2)_L$ singlet dark matter particles with SM EW gauge bosons

$$\mathscr{L}_\phi = C^\phi_{\mathscr{B}} \phi^2 B_{\mu\nu} B^{\mu\nu} + C^\phi_{\mathscr{W}} \phi^2 W^a_{\mu\nu} W^{a,\mu\nu}$$

$$\mathscr{L}_\phi = \phi^2 \left(\mathscr{C}^\phi_{\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + \mathscr{C}^\phi_{ZZ} Z_{\mu\nu} Z^{\mu\nu} + \mathscr{C}^\phi_{\gamma Z} Z_{\mu\nu} A^{\mu\nu} + \mathscr{C}^\phi_{WW} W^+_{\mu\nu} W^{-,\mu\nu} \right)$$

First operators that appear in the EFT expansion

Real scalar case

[1] *B. J. Kavanagh, P. Panci, and R. Ziegler JHEP 04 (2019) 089, [arXiv:1810.00033]*

Motivation

Elusive DM scenario for DD
⇒ no couplings with lighter dof $(q, \mathscr{G})$
⇒ Loop suppressed cross sections

Interesting target for Indirect Detection probes
- DM annihilates with γ
- FERMI works only up to $\mathcal{O}(500) GeV$

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How do we test this scenario at colliders?

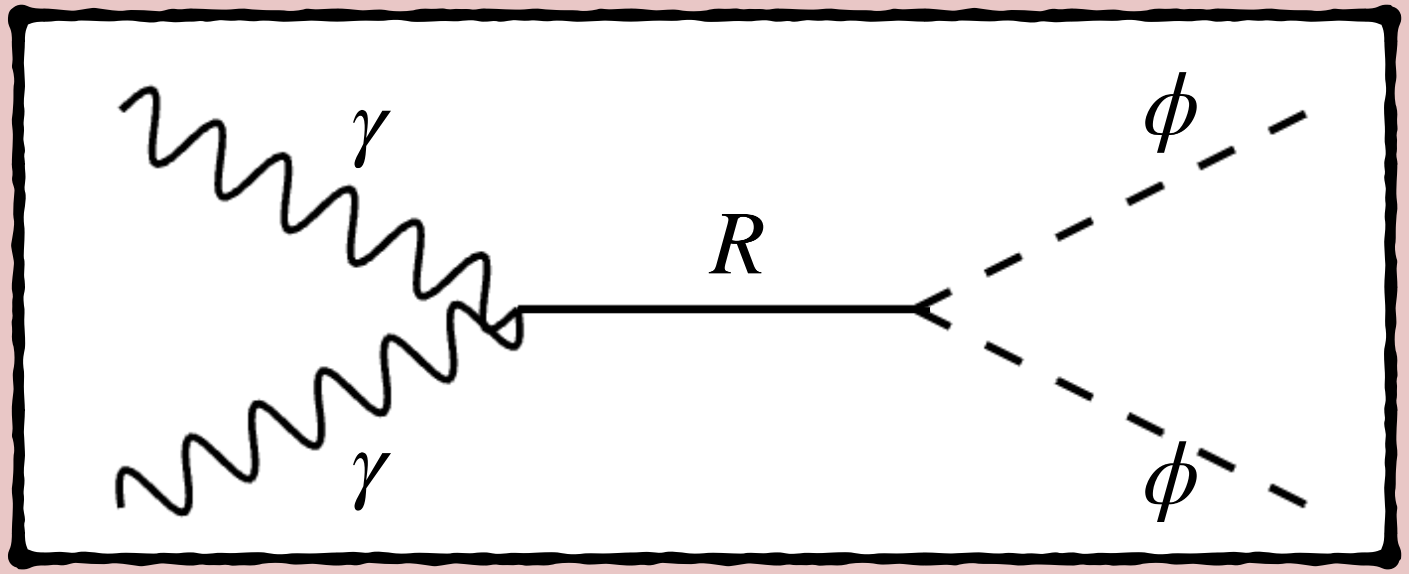
FCCee and FCChh

Could provide additional information about the model in the coming years

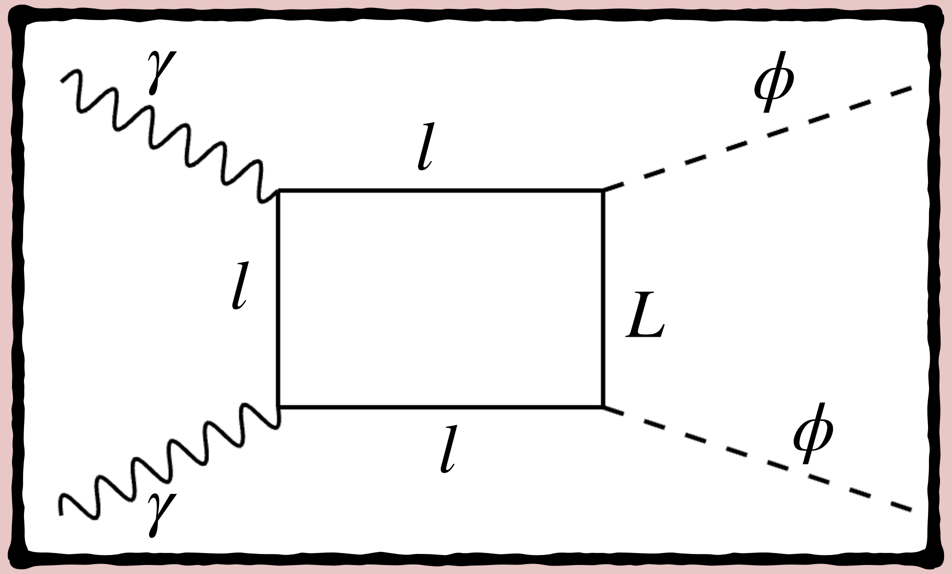
UV completion?

- Wilson coefficients are related to the scale where these operators are generated as $C^{\phi}_{\mathscr{B},\mathscr{W}} = \frac{c_{B,W}}{\Lambda^2_{B,W}}$
- UV completion can be achieved through:

Tree level: $\Lambda_{B,W} = \Lambda^{tree}_{B,W}$



Loop level: $\Lambda_{B,W} = \frac{4\sqrt{2}\pi}{g_{Y,2}}\Lambda^{loop}_{B,W}$



Experiments

1. LHC @ $\sqrt{s} = 13$ TeV, $L = 139/fb$ → HL-LHC $\sqrt{s} = 13$ TeV, $L = 3\ ab^{-1}$
2. FCC-hh @ $\sqrt{s} = 80{,}100$ TeV, $L = 30/ab$
3. Z-factory at FCC-ee ($L = 120/ab$)
4. μC @ $\sqrt{s} = 3{,}10$ TeV
5. Xenon and Darwin
6. FERMI

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Colliders

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Colliders

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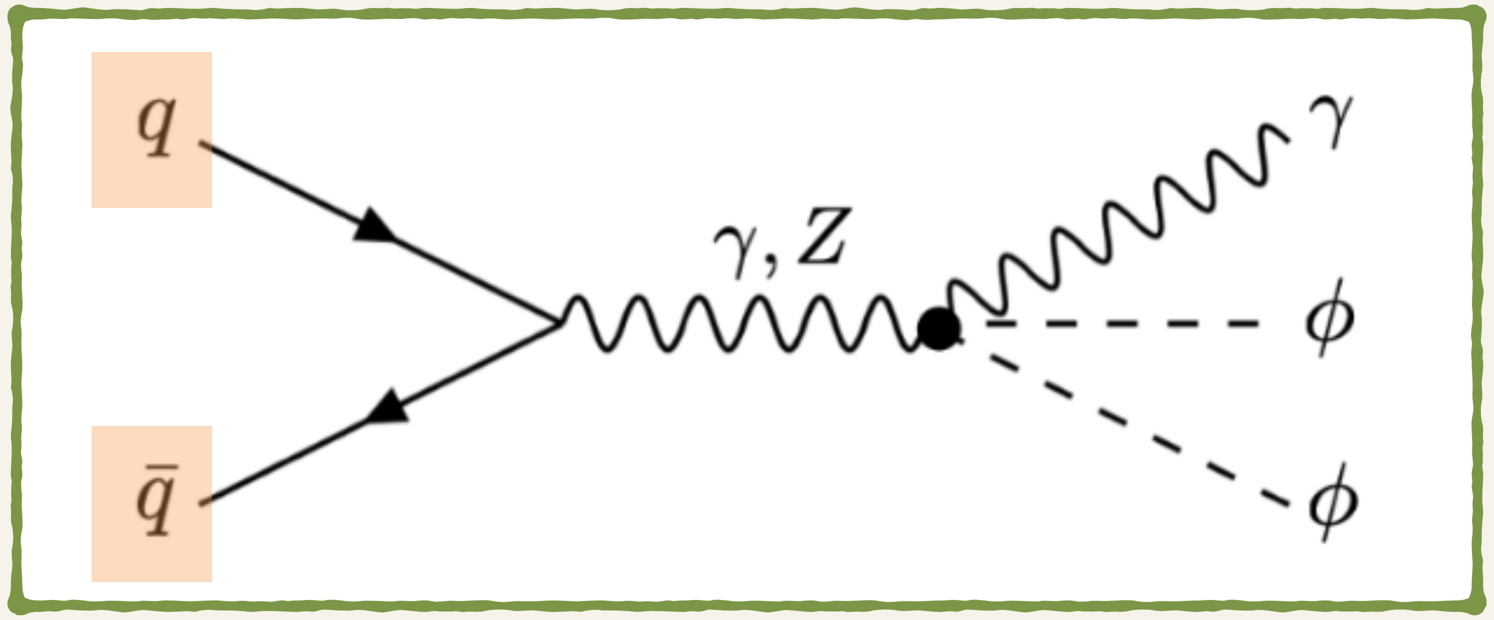
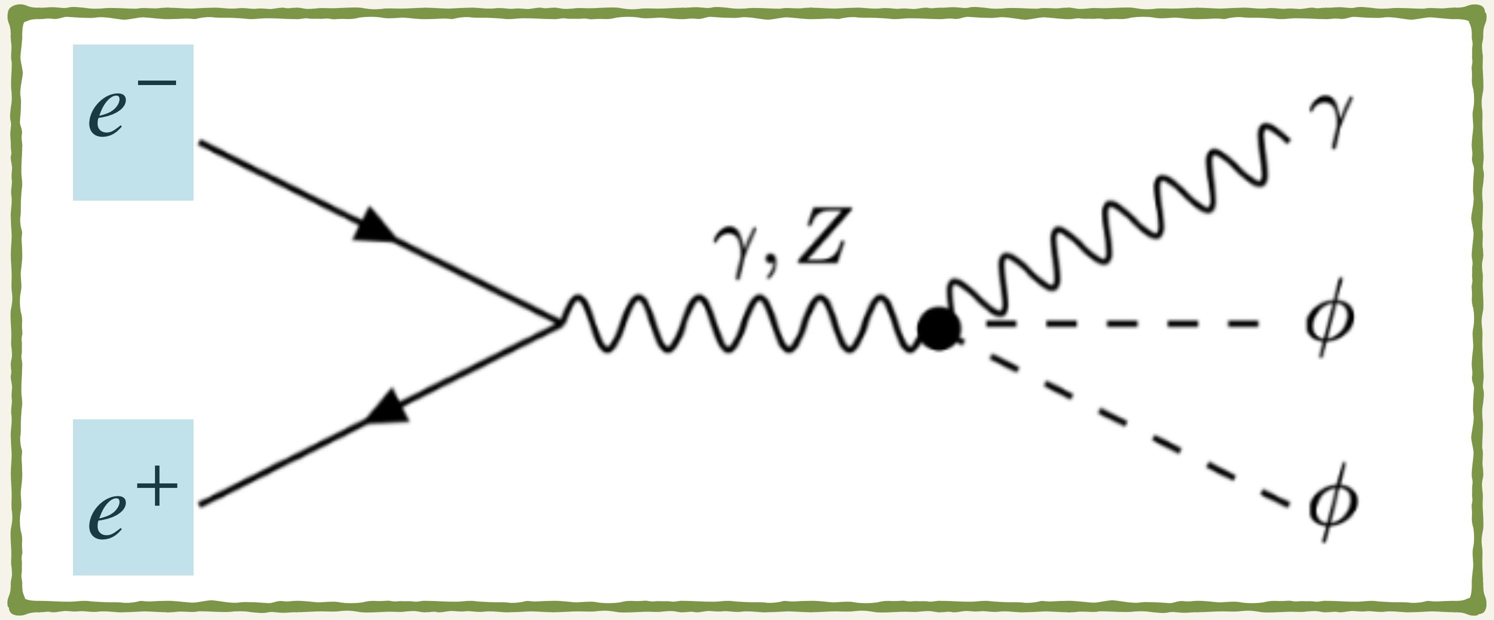
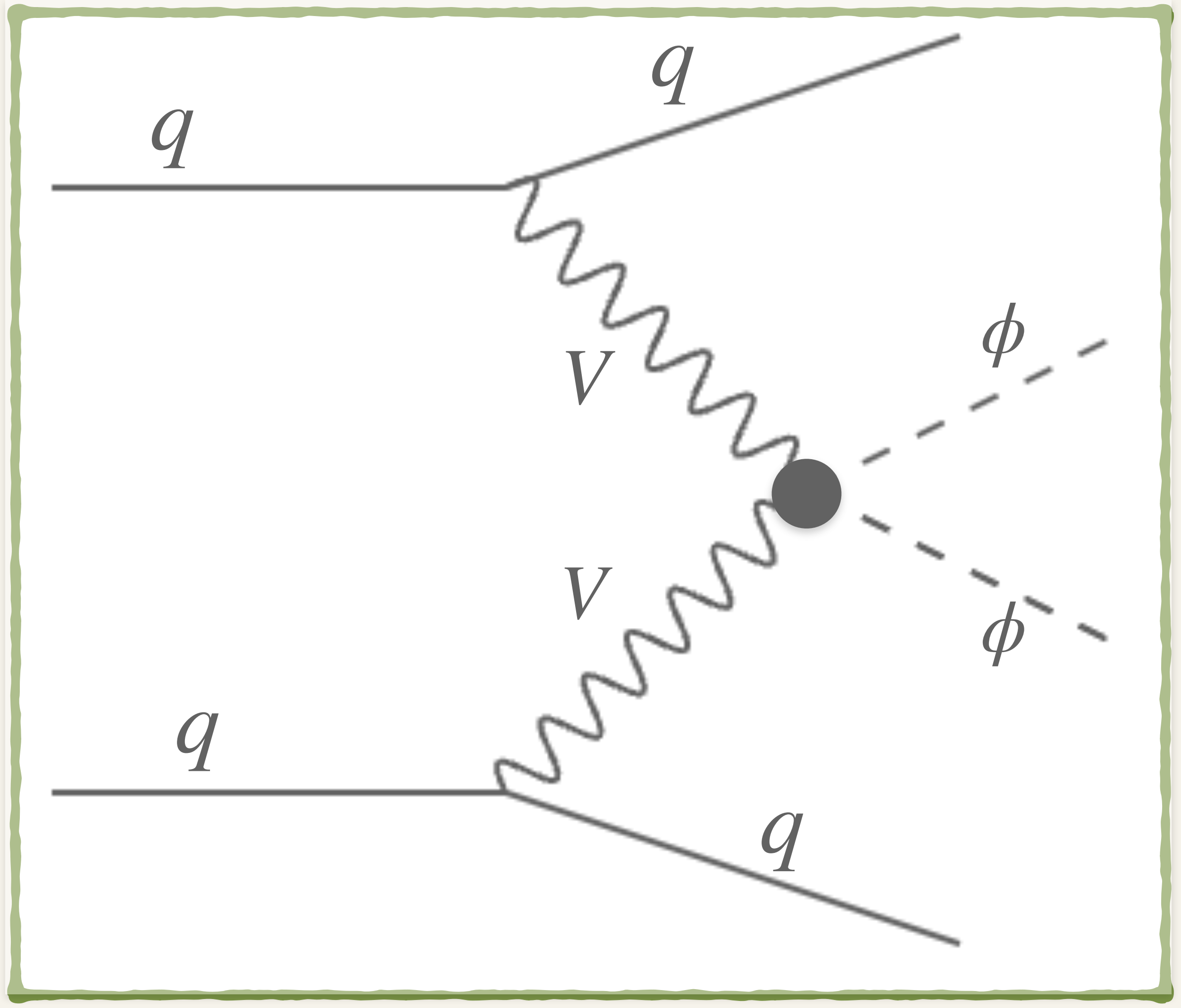
5. Xenon and Darwin — DD
6. FERMI — ID

Drell-Yan processes + Fusion TBD







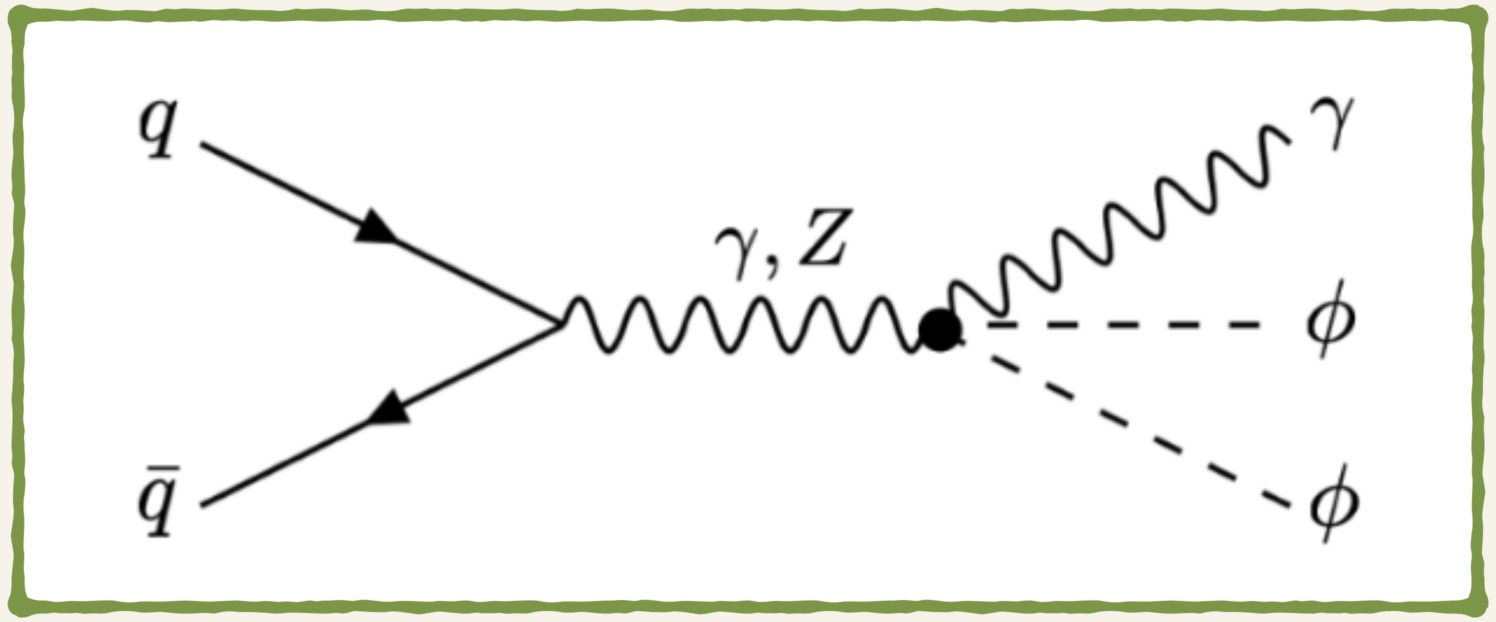
$\sqrt{s} = 13$ TeV

$L = 139\ fb^{-1} - 3ab^{-1}$

Colliders

1 LHC and high-lumi LHC: mono-γ analysis

- DM is produced in association with a high p_T^γ
- Recast the ATLAS analysis
- Work with LO Parton level for signal simulation



Analysis selections

ATLAS: 2011.05259

7 SRs defined with increasing MET

$E_T^\gamma > 150$ GeV and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$

SRI1	SRI2	SRI3	SRI4	SRE1	SRE2	SRE3
> 200	> 250	> 300	> 375	$200 - 250$	250-300	300-350

Validity of the EFT

$$\mathscr{L}_\phi^{strong} = \tilde{C}_B^\phi \phi^2 B_{\mu\nu} B^{\mu\nu} + \tilde{C}_W^\phi \phi^2 W_{\mu\nu} W^{\mu\nu}$$

we require that $p_T^\gamma < \Lambda$

Projections for high-lumi LHC

- Assume only statistical uncertainties and same selections of ATLAS analysis
- 95% CL bound with $\frac{N_S}{\sqrt{N_B}}$ rescaling the expected SM events by lumi ratio

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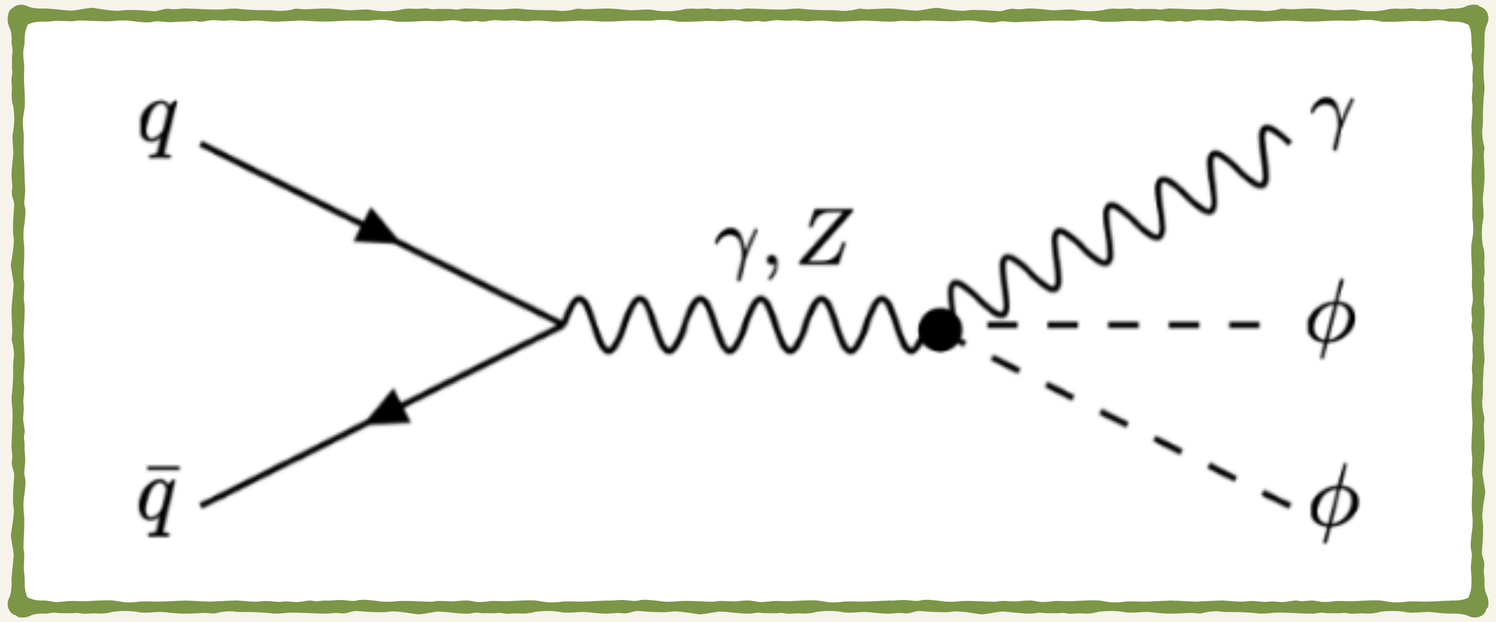

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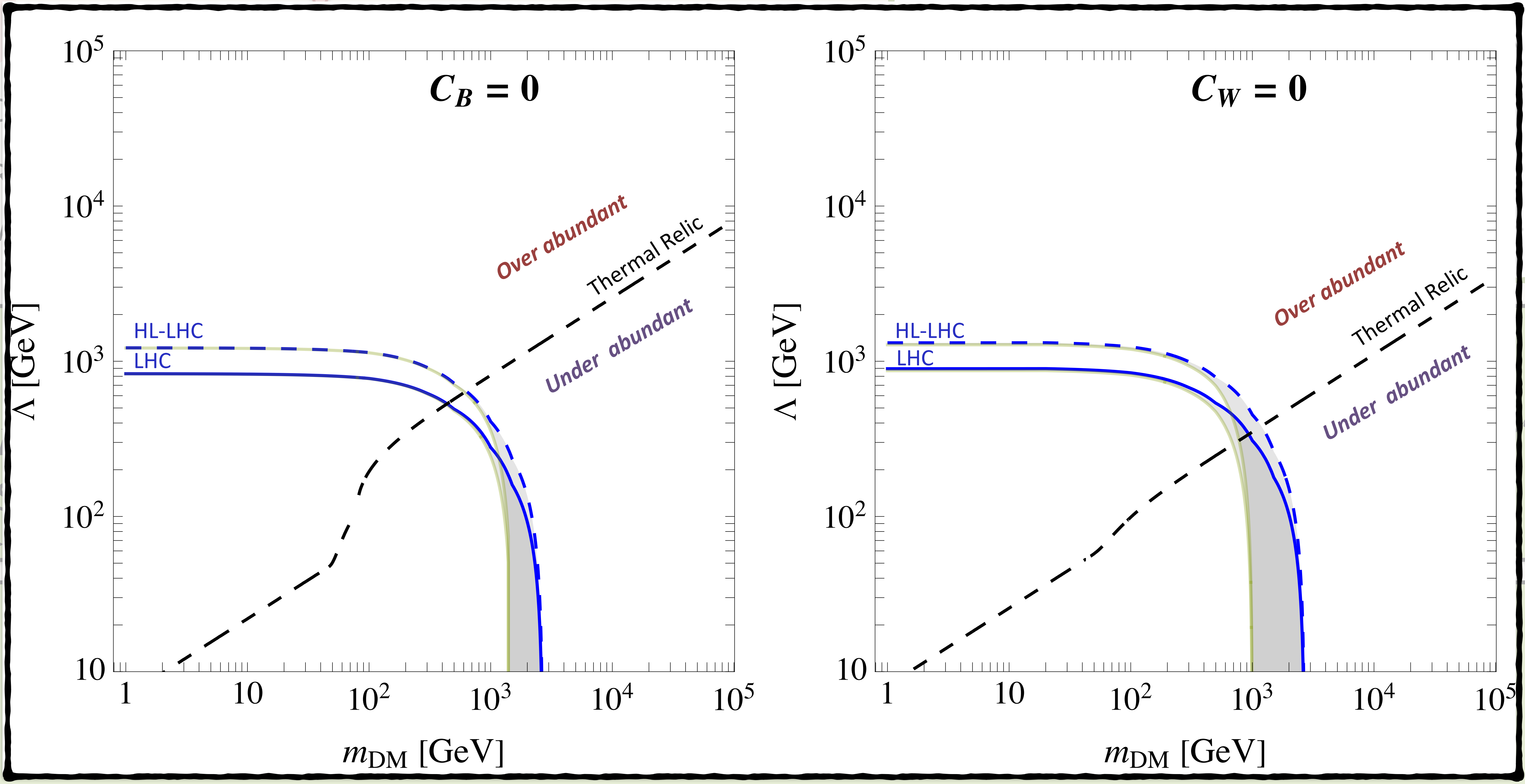

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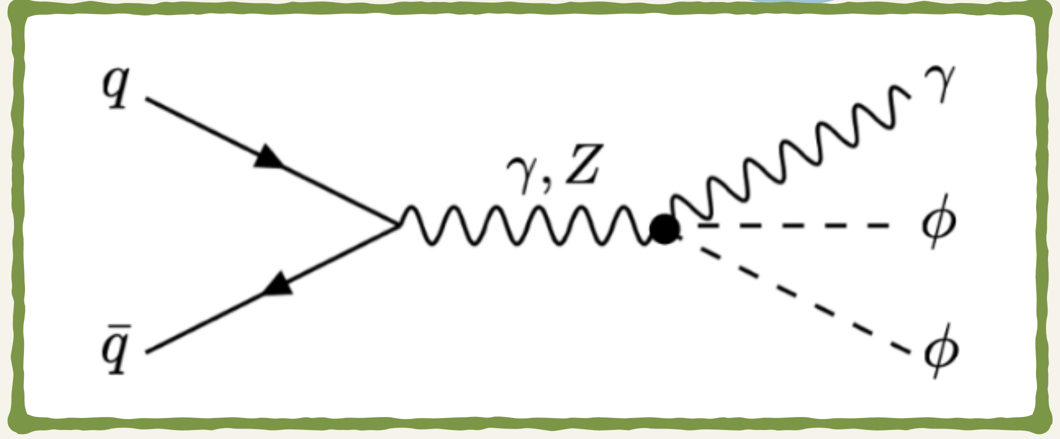


2 **FCC-hh**: DY process - @ 80/100 TeV with $L = 30\ ab^{-1}$

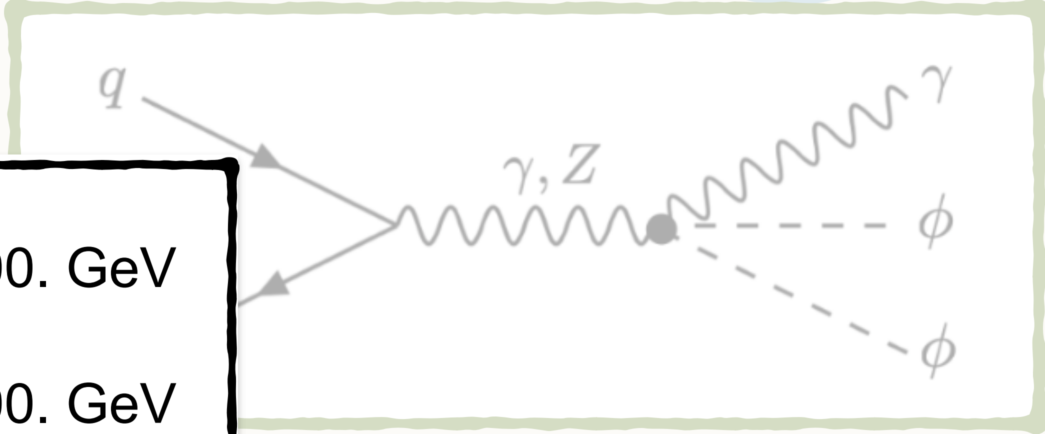
- Process assumed to be qualitatively the same as ATLAS mono-γ
- Hard photon $\Rightarrow$ different analysis wrt the soft photon analysis already done
- The $pp \to Z\gamma, Z \to \nu\bar{\nu}$ channel is the dominant bkg

$\Rightarrow$ $\sim 60\,\%$ of the total yield $(bkg)^{ATLAS}_{\nu}/(bkg)^{ATLAS}_{tot}$

- LO simulation with MadGraph for ν channel in the fiducial regions given by ATLAS
  - We find that the LO $Z\gamma$ simulation accounts for $\sim 80\,\%$ of the experimental $Z\gamma$ ATLAS background and hence $\sim 50\,\%$ of the total experimental background

  $\Rightarrow$ this is constant in all the ATLAS signal regions;
  - We estimate the total SM bkg multiplying by a factor 2 the dominant $Z\gamma$ bkg computed using MadGraph;
- <u>Signal selection:</u> $|\eta| < 2.37$ and we optimize on the MET requirement

Colliders



2 **FCC-hh**: D

- Process assumed to
- Hard photon ⇒ dif
- The $pp \to Z\gamma, Z \to$

⇒ $\sim 60\,\%$ of the to

- LO simulation with
  - We find that the … ATLAS
    background and
  ⇒ this is constant
  - We estimate the … nputed
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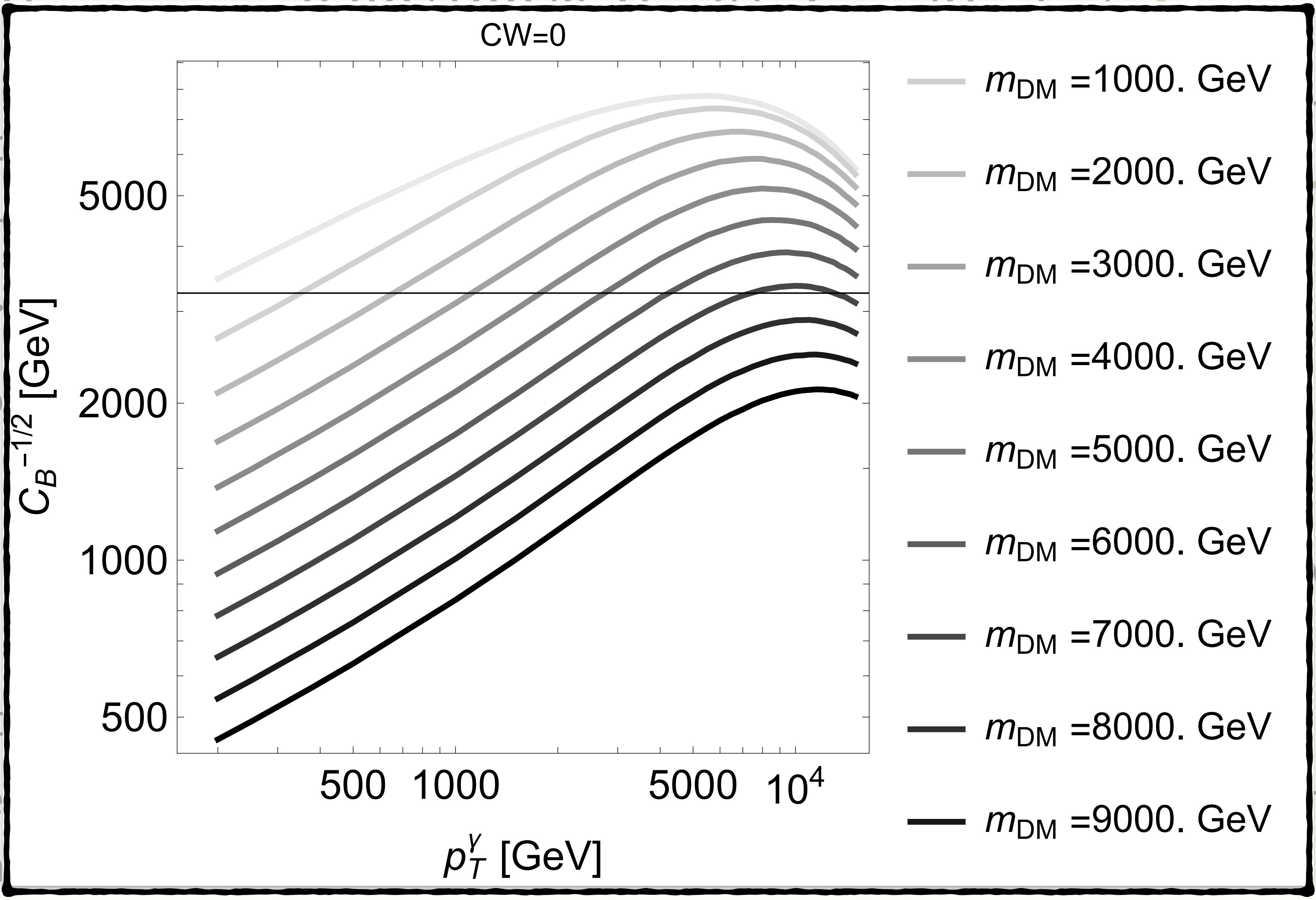

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Colliders

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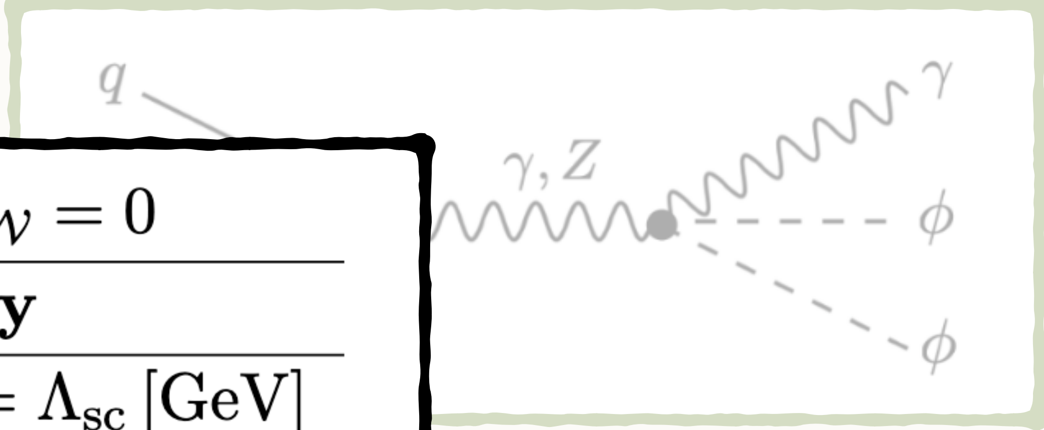


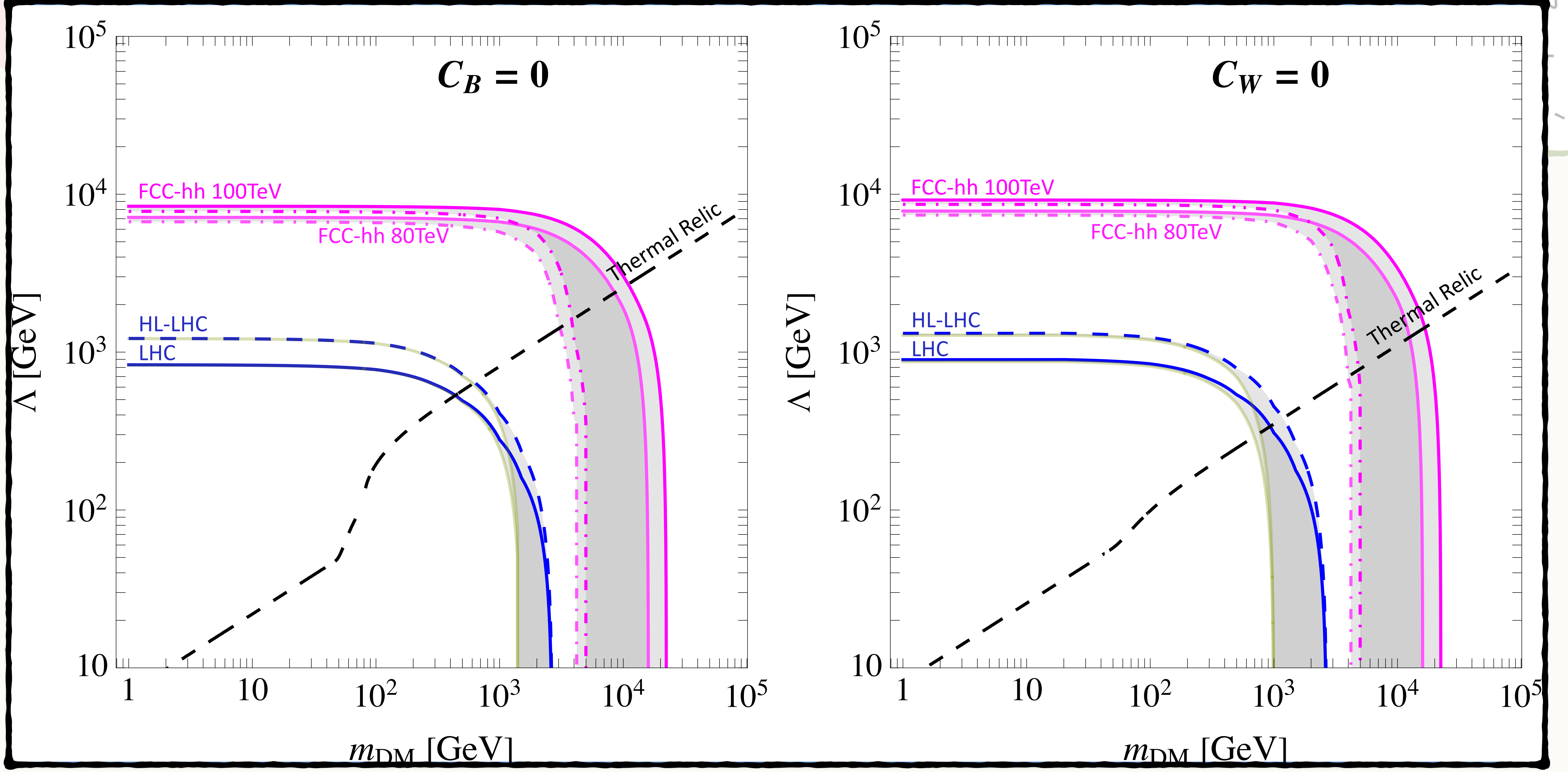
mono−γ DY at FCC-hh $\sqrt{s} = 80\,\text{TeV}$ $\mathcal{L} = 30\,\text{ab}^{-1}$ $\tilde{\mathcal{C}}_{\mathcal{W}} = 0$

	No EFT validity		**EFT validity**	
m_ϕ [GeV]	$p_{T,\text{min}}^{\gamma}$ [GeV]	Λ_{sc} [GeV]	$p_{T,\text{min}}^{\gamma}$ [GeV]	$p_{T,\text{max}}^{\gamma} = \Lambda_{\text{sc}}$ [GeV]
100	5500	7780	4000	7300
1000	6000	7350	4000	6650
2000	6500	6640	3500	5100
5000	8500	4490	200	250

mono−γ DY at FCC-hh $\sqrt{s} = 100\,\text{TeV}$ $\mathcal{L} = 30\,\text{ab}^{-1}$ $\tilde{\mathcal{C}}_{\mathcal{W}} = 0$

	No EFT validity		**EFT validity**	
m_ϕ [GeV]	$p_{T,\text{min}}^{\gamma}$ [GeV]	Λ_{sc} [GeV]	$p_{T,\text{min}}^{\gamma}$ [GeV]	$p_{T,\text{max}}^{\gamma} = \Lambda_{\text{sc}}$ [GeV]
100	7000	9150	4500	8500
1000	7500	8800	5000	7900
2000	8000	8160	4500	6600
7000	11000	4850	300	380

Colliders



$C_B = 0$
$C_W = 0$
FCC-hh 100TeV
FCC-hh 80TeV
HL-LHC
LHC
Thermal Relic
Λ [GeV]
m_{DM} [GeV]

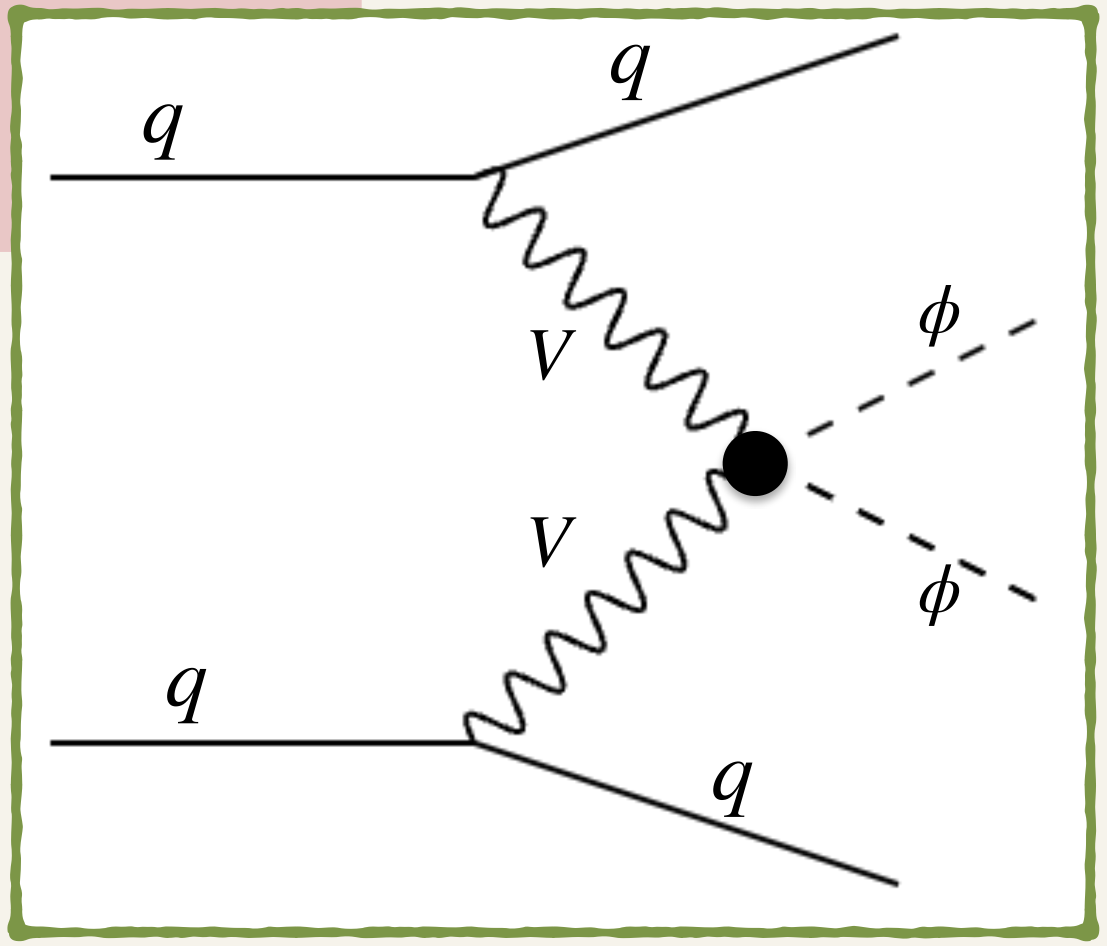
Colliders

2+ **FCC-hh**: Forthcoming studies

VBF Analysis

- VBF is a relevant process ⇒ different kinematics
- We would like to perform a forward production analysis

⇒ No clean environment!



BEFORE FCC-hh

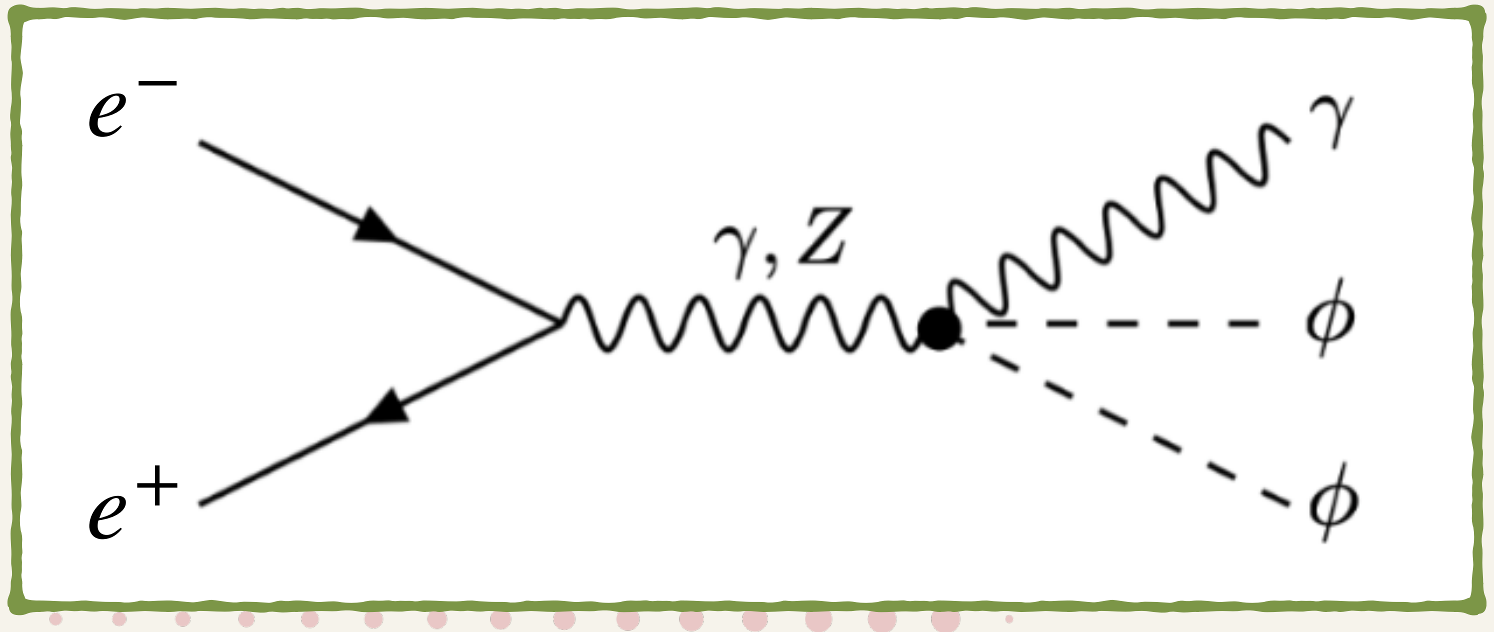
Colliders

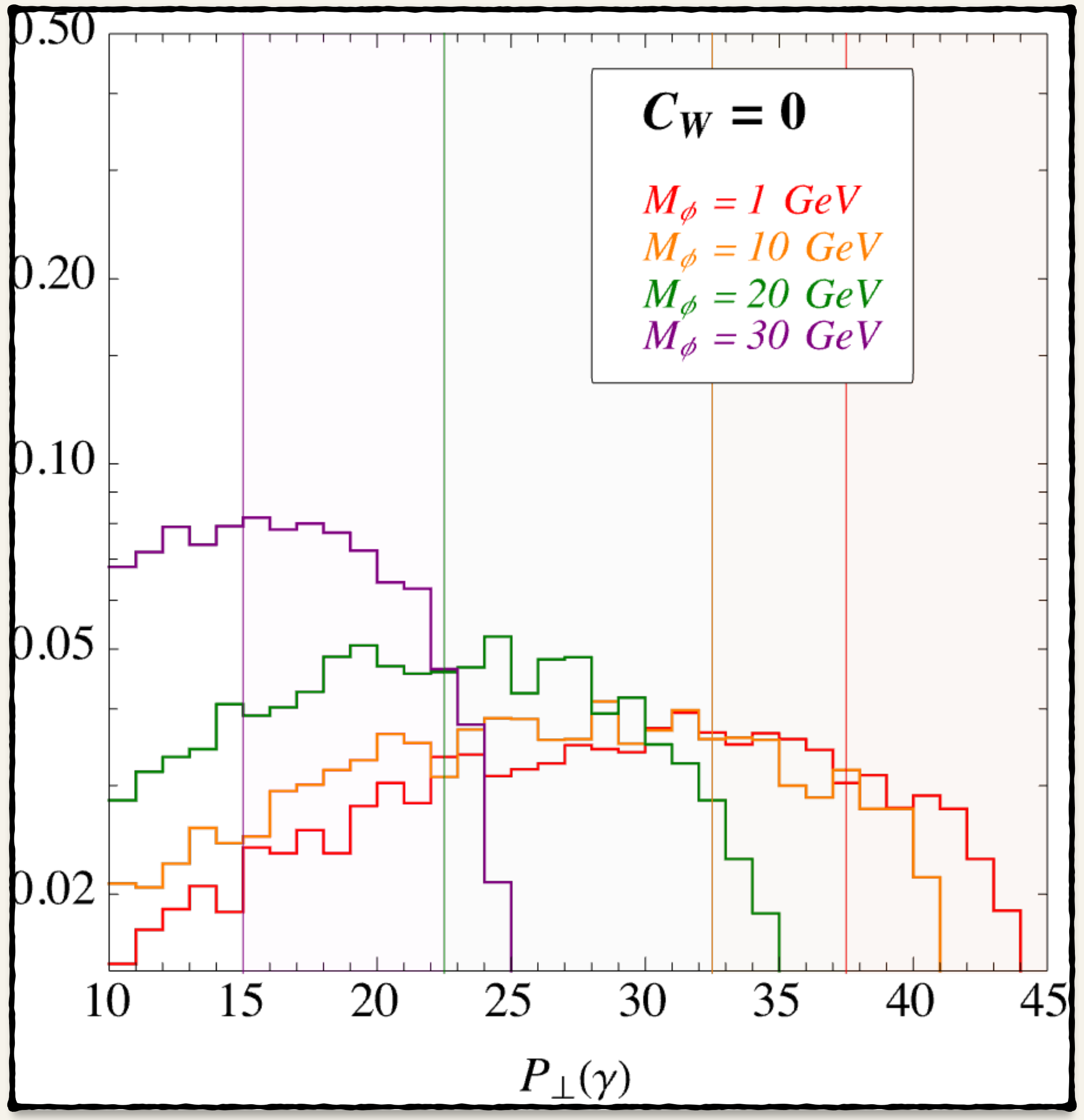
$\sqrt{s} = 91.2\,\text{GeV}$

$L = 120\,ab^{-1}$

3 **FCC-ee:** DY process

- Z-pole to probe the scale Λ ⇒DM produced in association with an energetic photon
- Strongest sensitivity from on-shell Z
- The dominant bkg is $e^+e^- \rightarrow \gamma\nu\bar{\nu}$
- Analysis selections: we have taken $|\eta| < 2.5$
- We maximize the sensitivity $\frac{N_S}{\sqrt{N_B}}$ adding a cut on P_T^γ





Colliders

$\sqrt{s} = 91.2$ GeV
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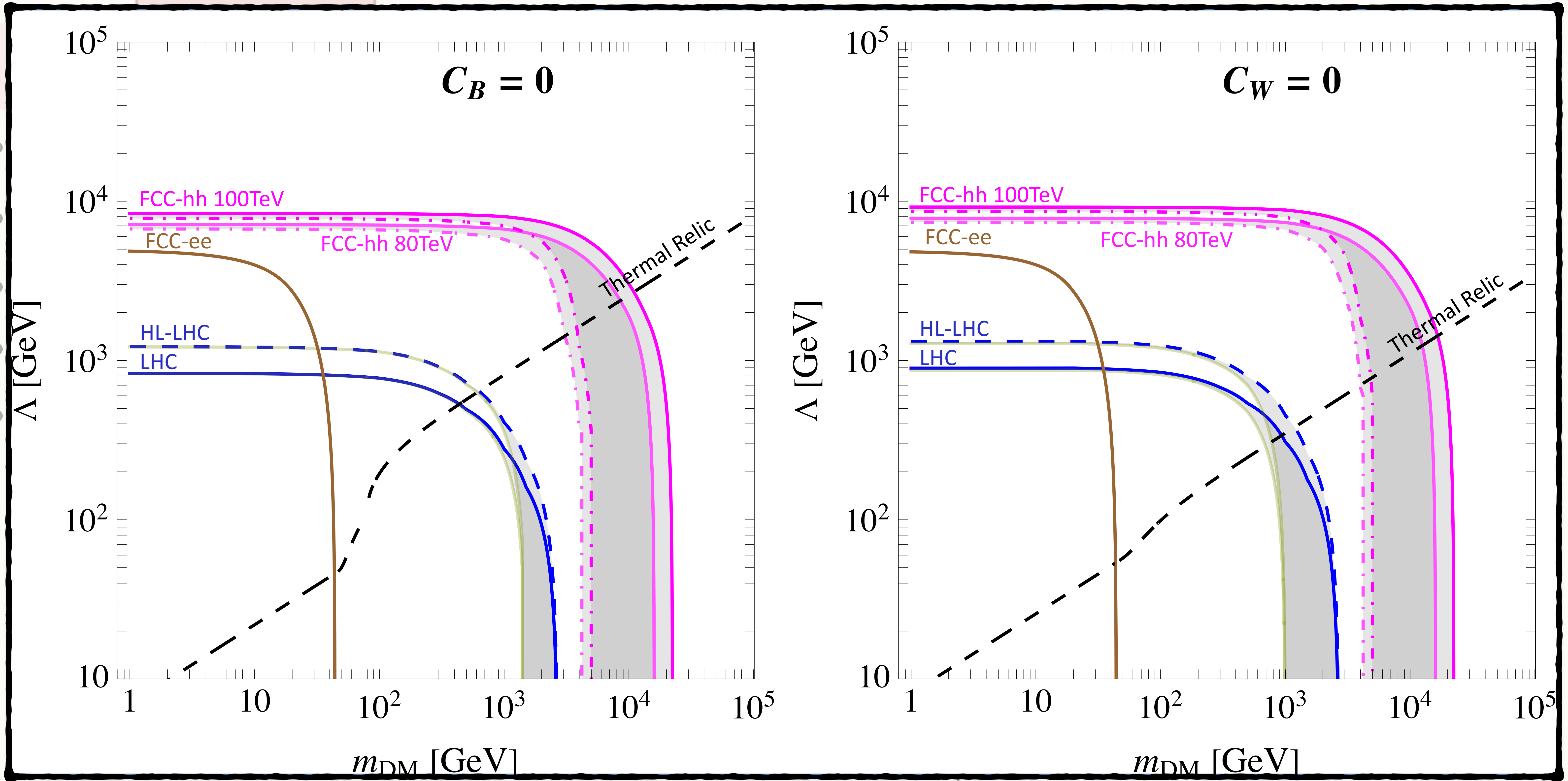


10 15 20 25 30 35 40 45
$P_\perp(\gamma)$

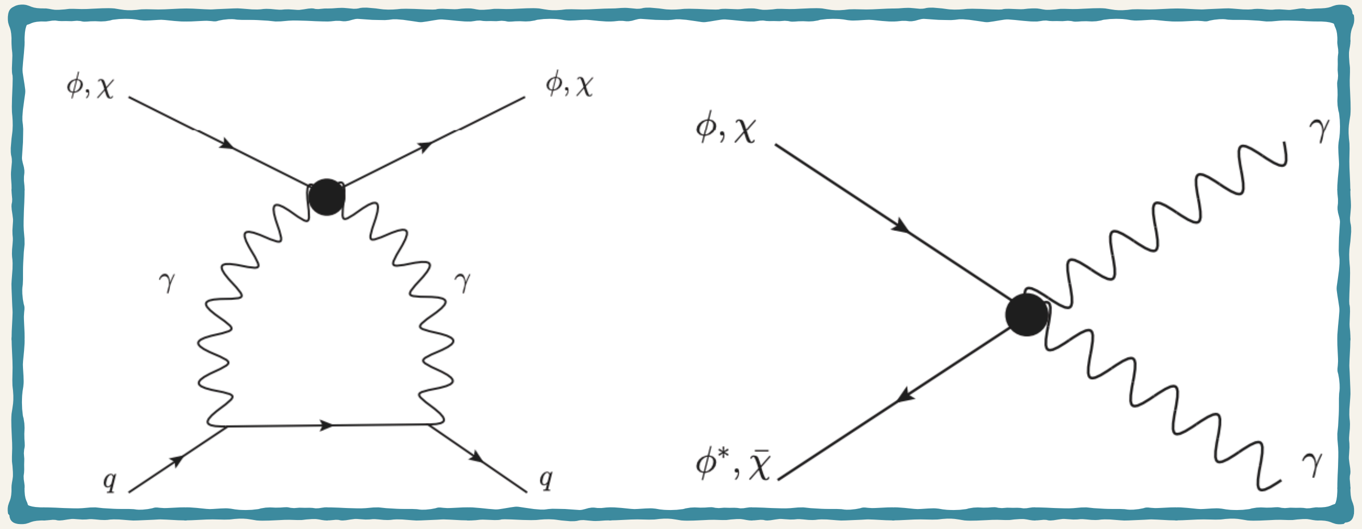
DD and ID

Kickoff Meeting | 2024

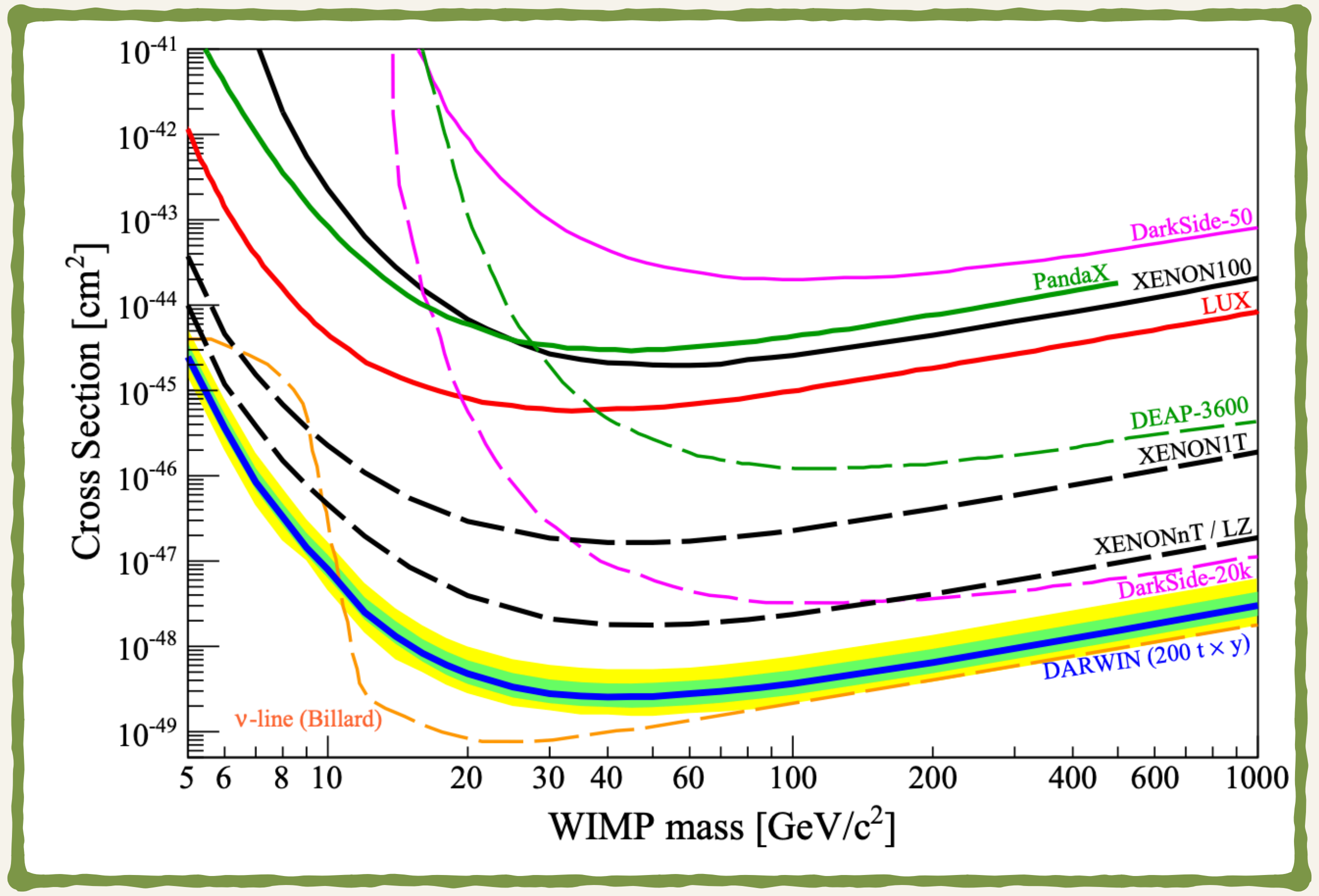
5 Xenon and Darwin

$$\frac{d\sigma^{Ray}}{dE_R} = \frac{4m_T}{m_\phi^2 v^2}\frac{c_{\gamma\gamma}}{\Lambda^4}\frac{Z^4\alpha_{em}^2}{\pi^2 b^2(A)}\mathscr{F}_{ray}^2$$

$$\frac{d\sigma^{SI}}{dE_R} = \frac{m_T}{2\mu_{\phi T}^2 v^2}\sigma_{SI}^n \mathscr{F}_h$$



PRD 131,041003 and arxiv:1606.07001



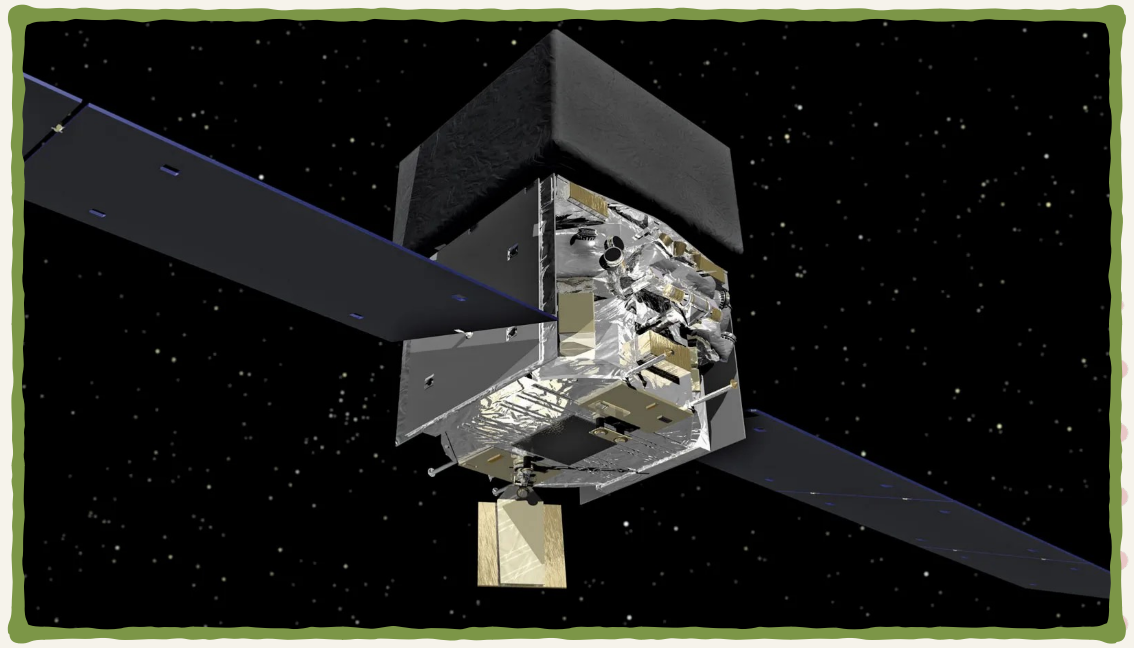
6 FERMI

- 840 weeks of data (08/2008-07/2024)

$0.7\,GeV < E_\gamma < 500\,GeV$

- ROI41: Most profile independent
- DM annihilation (*PPPC4MID Tool)*

Line($\phi\phi \to \gamma\gamma, \gamma Z$) + Continuum($ZZ, WW, \gamma Z$)



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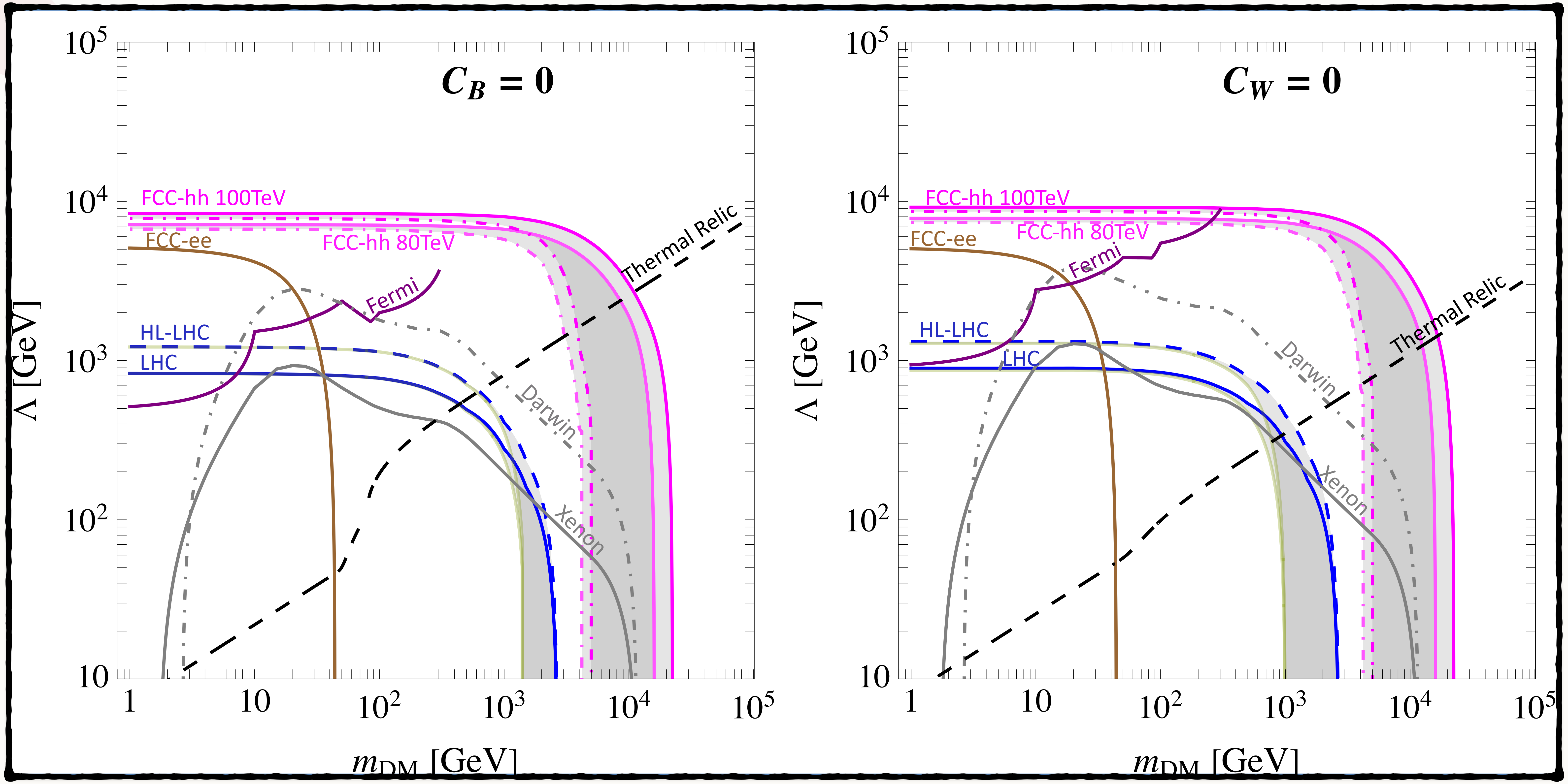

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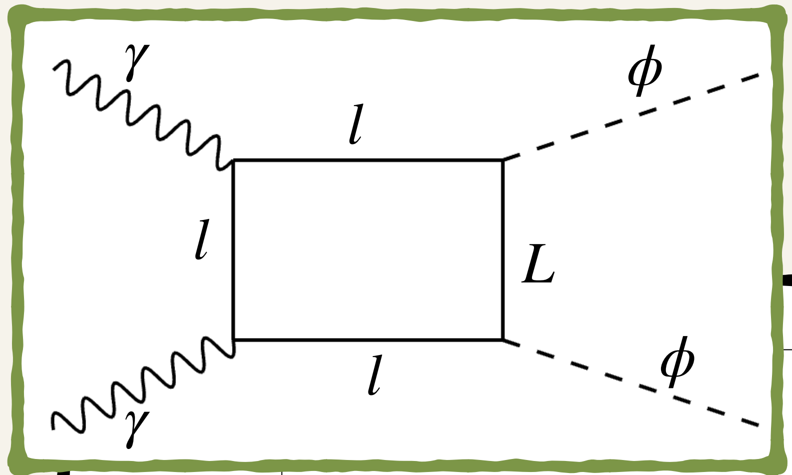
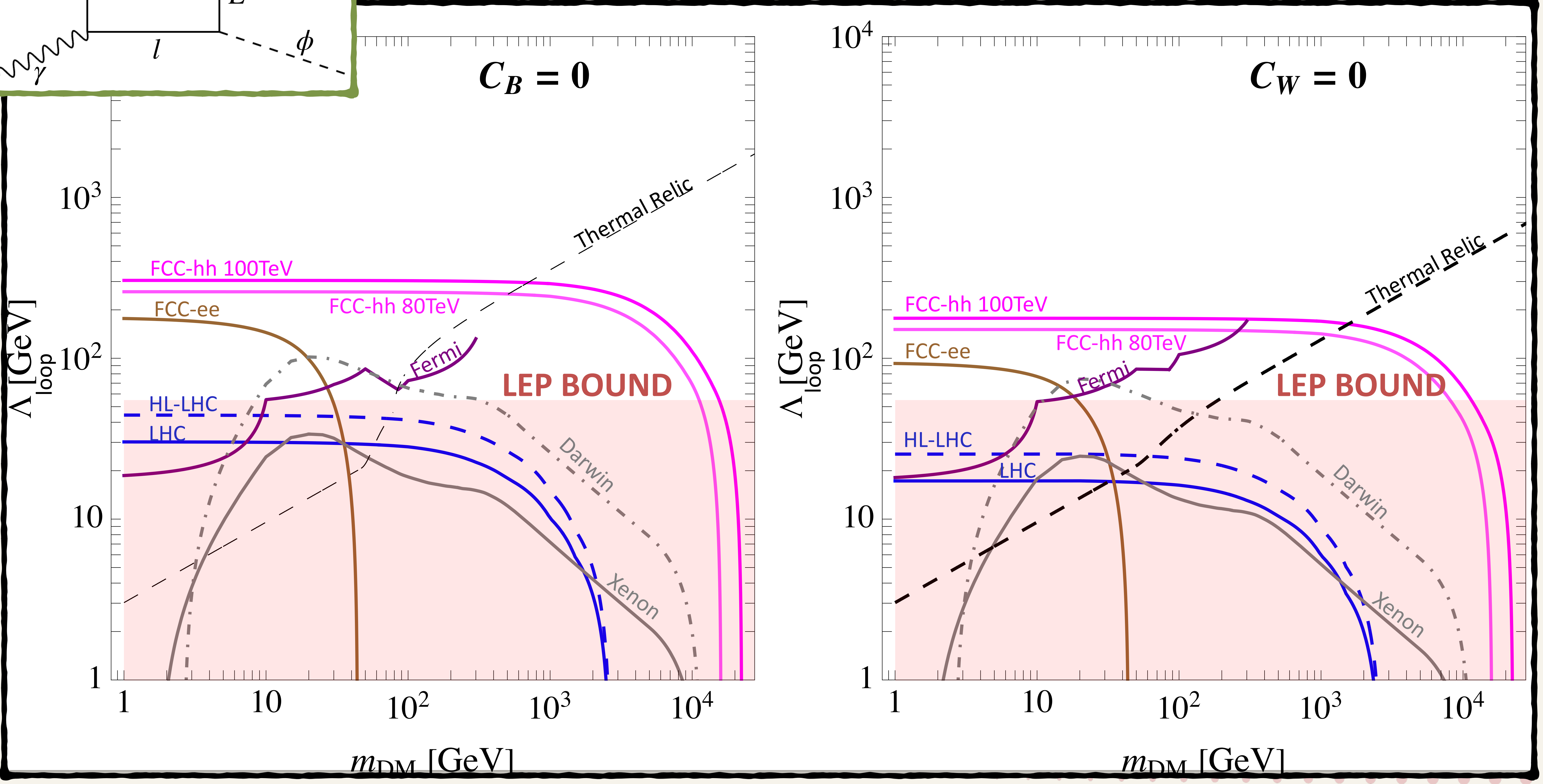


Loop Rescale

$$\Lambda_{B,W} = \frac{4\sqrt{2}\pi}{g_{Y,2}}\Lambda^{loop}_{B,W}$$



Conclusions

Near Future (FCCee, HL-LHC):

- Will place more stringent bounds on this dark matter scenario;
- FCCee gives one of the stringent bound, but only for small DM mass;
- HL-LHC will not be significantly greater than current LHC bounds.

Indirect and Direct Detection:

- Current bounds (e.g., FERMI) and future projections (e.g., Darwin) will remain competitive, if not stronger, than FCCee or HL-LHC.

Next Future (FCChh):

- Will be able to probe much higher energy scales;
- Could provide crucial insights into this dark matter benchmark.
- Forthcoming studies for VBF!

THANK YOU